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COGNITIVE TUTORS: CONCEPTUAL ARCHITECTURE AND EFFICIENCY

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Abstract

This article reviews the development of Intelligent Tutoring Systems (ITS) by focusing on the analysis of Cognitive Tutor (CT) application, relevant theoretical principles and effects of their use in formal education. The aim of this analysis was to examine the key building blocks of cognitive tutors and describe the way this software enhances the improvement of educational process. Important theoretical aspects of ACT-R theory and other relevant conceptual elements of Cognitive Tutors such as model-tracing mechanism along with parallel scrutinizing the efficiency of these theories and principles in the form of cognitive tutors are discussed in this paper. In this paper the results of relevant experimental studies in which the efficiency of cognitive tutors were tested after their implementation in the formal curriculum had been analyzed. The results were compared with the ones collected in the traditional way of teaching. It was shown that the use of cognitive tutors in formal education in comparison with traditional (group) way of teaching leads to a higher level of achievement and better understanding of the subject matter.

INTRODUCTION

Intelligent Tutoring Systems (ITSs) have built in mechanisms for learning process individualization in the regime of one-on-one learning providing timely feedback with the ability to demonstrate the solutions for the given problems (Jaques, Seffrin, Rubi, Morais, Guilardi, Bittencourt, & Isotani, 2013). There are many forms of ITS systems and many years of work on their development have caused the emergence of different types of such systems. In this paper the subject of discussion was the analysis of the functionality and efficiency of cognitive tutors. The primary role and the ability of cognitive tutors is oriented towards inducing the process of continual development of students by adjusting it to their individual abilities and propensity but also to track a student's progress over time and guide them efficiently through the learning process. As such, these systems can contribute to the improvement of level of student achievement compared to the shortcomings of traditional (group) way of teaching and learning.

In the past four decades a great deal of effort has been invested in the development of the system theories which connected a wide variety of multidisciplinary areas such as: behavioral psychology, cognitive science, information technology, artificial intelligence and many other fields in order to design systems that would enable better and more natural human-machine interaction.

The focus of the research in this paper was on determining the conceptual architecture of cognitive tutors along with parallel analysis of its efficiency by using the method of comparative analysis of relevant empiric studies. The purpose of this research was examining the level of efficiency of the application of cognitive tutors in traditional teaching.

Theoretical hypotheses which the principle of Cognitive Tutors functioning is based on are discussed in the paper and then compared to the results of the studies conducted in order to determine the differences between traditional group teaching and individually oriented teaching by using Cognitive Tutors.

Numerous empiric evidences pointing out to the fact that the efficiency of Cognitive Tutors can be much higher in comparison to traditional group way of teaching are discussed in this paper.

Kodaganallur, Weitz and Rosenthal (2005) analyzed the efficiency of cognitive tutors and interpreted the results of the research conducted by Koedinger and Anderson (1997) described in the study which had included the comparative analysis of Cognitive PUMP Algebra Tutor and the traditional form of teaching which determined the presence of improvement in achievement of one standard deviation. (p.3).

Numerous experimental analyses confirm the efficiency of Cognitive Tutors, but they still can't achieve the level of efficiency that human tutors can in one-to-one form of teaching (Bloom, 1984), although they can be used as an adequate and very efficient substitute tool for the improvement of efficiency in the critical fields of science.

INTELLIGENT TUTORING SYSTEMS

In search for the efficient principles of "Group Instruction" teaching Anania and Burke conducted the research made of an efficiency test which was applied on a "conventional" group containing 30 students studying in traditional education environment with one teacher; the achievements of the group were measured periodically with tests of knowledge. The same test and methodology was applied on the "Mastery Learning" group which differed from the conventional group only in the feedback effect followed by certain corrective procedures within the frames of parallel formative tests. Finally, "Tutor Group" to which the results of the final achievements were compared had two specific characteristics: to each of 30 students in the group a personal tutor was assigned and every student's test result was followed by a timely feedback as well as the adequate form of the corrective measurements depending on the students' answers (Bloom, 1984). In the end of the research it was determined that the achievements of the students in the "Tutor Group" compared to the control (conventional) group were within 2 standard deviations above the mean (98%) while the values of the "Mastery Learning" group were 84% (Bloom, 1984). It was concluded that individual teaching one-to-on provides far better results compared to the traditional group method (Kenneth & Koedinger, 2006).

During the past four decades many researches have been done in the domain of the application of artificial intelligence in the development of Intelligent Tutoring Systems able to "imitate" the characteristics of human tutors as well as adapt to the set of individual differences of students based on their achievements, abilities and other relevant characteristics (Ahuja and Sille, 2013). One of the first systems of this kind was "The SCHOOLAR System" developed by J. R. Carbonell in the U.S.A. in the 1970. (Freedman, 1997). The original tutoring systems had had modest possibilities: low level of man-machine interaction which later on developed into more sophisticated and complicated forms connecting multiple disciplines: artificial intelligence, informatics, pedagogy, psychology, etc., followed by the division of their development approach and the principles of their implementation (Ahuja and Sille, 2013).

COGNITIVE TUTORS

The set of integral parts and relevant theories which the functionality of Cognitive Tutor is based on shall be analyzed in further discussion. According to Koedinger & Aleven (2007) “Cognitive Tutors are a type of intelligent tutor based on cognitive psychology theory of problem solving and learning”. The common characteristic of all cognitive tutors is their functional foundation on the cognitive model which is an expert system that enables cognitive tutors to solve problem questions in the same way as students do (Corbett, McLaughlin, & Scarpinatto, 2000).

The conceptual architecture of cognitive model is based on the principles of ACT-R (Adaptive Control of Thought – Rational) theory implying componential separation of declarative and procedural knowledge (Corbett, McLaughlin, & Scarpinatto, 2000). Declarative knowledge includes the theoretical understanding of the facts on the matter, procedural knowledge integrates relevant functionally based theoretical principles transforming them into a form of practical operations (Ritter, Anderson and Koedinger, 2007). One might say that the application of the method of componential analysis of theoretical forms of the matter knowledge along with procedural principles are what the functional form of knowledge is made of and that is the main characteristic of all cognitive tutors.

The foundation of ACT-R architecture on which most of cognitive authors are based on enables periodical testing of projected curriculum on practical basis by direct implementing of tutors in teaching. Cognitive tutor periodically observes the work of students in equal time intervals, continually grades their work and, based on that, forms predictions about the level of knowledge in the domain of studying. Assumptions about the quality of the cognitive model shaping student behaviour can be finally formed on the basis of the collected information. (Ritter, Anderson & Koedinger, 2007).

Kenneth & Koedinger (2006) point out that: “Cognitive Tutors support learning by doing, an essential aspect of human tutoring” (p. 2). Numerous empiric indicators which are discussed in this paper show the efficiency of the application of cognitive tutors in traditional teaching, however, achieving higher efficiency in the process of the implementation of teaching material on the quantitative level is not the goal by itself. The purpose of the application of cognitive authors in formal teaching is connecting the theoretical basis, hypotheses and facts with practical knowledge and skills in a certain domain in order to achieve complete, functional understanding of the teaching material.

COGNITIVE TUTOR: CONCEPTUAL MODEL

Anderson, Corbett and Koedinger (1995) suggested that Cognitive Tutor must have implemented "Model" whose role is to generate a string of componential sequences representing the expected outcome for the given problem (p. 117). Through a user interface students are able to answer affirmatively to the assigned problems which the system is suppose to identify as a form of accurate actions ("On-Path-Actions") as long as they are in accordance with the predetermined path of moving through the system leading to the goal. Also, the system is suppose to identify all forms of deviation ("Off-Path-Actions"), correct them and bring a student back to the right path (Anderson, Corbett and Koedinger, 1995, p.171). Students are not expected to always provide correct answers (which was the main characteristic of the original intelligent tutors), nor to strictly follow the formal path through the system, so, the "Error Feedback and Help" component's purpose is identifying all deviations from the path and suggest a student an alternative approach to solving a problem. A student also has the possibility of asking help in any moment when he'll get hints, suggestions or actions which are appropriate for solving a certain problem (Anderson, Corbett and Koedinger, 1995, p.172).

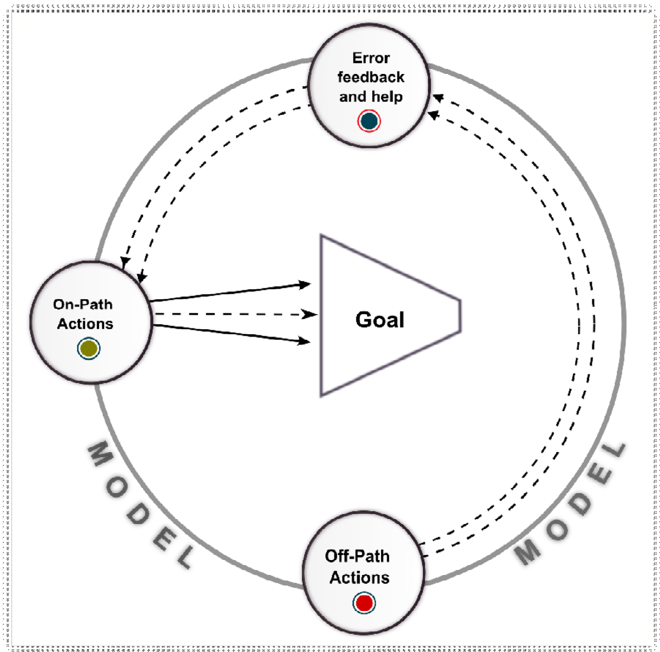

Figure 1. Model tracing mechanism

Cognitive tutors are based on the application of model-tracing; this tutor is called Model Tracing Tutor (MTT) (Kodaganallur, Weitz & Rosenthal, 2005). Model-tracing is an algorithm which traces a student's actions during solving a given problem. The algorithm is implemented in the structure of the model and its purpose is supervising specific steps of a student, giving assistance when necessary and providing guidance towards solving a problem. The system is able to supervise specific steps of students as well as provide an adequate form of assistance whenever a deviation is detected. After the identification of a deviation the mechanism generates an assistance by suggesting a general principle of solving the problem; after evidenting the right answer to a certain problem the student is redirected to the next step of the program (Koedinger & Corbett, 2006).

THE CONCEPTION OF ACT-R THEORY

In the previous part of the paper in the interpretation of the basic structural factors of Cognitive Tutor the significance of componential differentiation between declarative and procedural knowledge as an important integral part of ACT-R theory mechanism (Adaptive Control of Thought – Rational) was pointed at in a rather abstract level.

ACT-R theory is a computer model of cognitive architecture. This theory provides the foundation for computer systems development able to emulate and predict human forms of behaviour. The conceptual model of ACT-R theory can be broken down into a group of a modular set components. Each component of the system is made of a unique module which performs the operations defined in advance. Every operation is inherent to a certain module and the information processing on the level of modules is organized through a set of individual buffers (Qin, Bothell and Anderson, 2007).

Building blocks of ACT-R theory

In the introductory parts of the paper it was pointed out to the significance of procedural knowledge which a man displays through his behaviour. Procedural forms of knowledge are complex forms which a man displays every day through his behaviour while speaking, driving a car, etc. However, it's hard for a man to interprete the principles which regulate these processes. The procedural forms of knowledge within ACT-R theory are organized into a set of rules called "Productions". Contrary to procedural knowledge, the second important component of ACT-R system is a declarative form of knowledge which is a more simple form of knowledge organized into structures called "Chunks". Finally, "Productions" and "Chunks" make functional building blocks of ACT-R theory (Qin et al, 2007).

ACT-R theory: system components

Cognitive skills can be continually structured by using conditional declarations within ACT-R system which are called Production Rules. Semantically speaking, the term Production Rules is used for signifying the form of a declaration structured by applying Lisp syntax which describes the action which a student is suppose to undertake for the purpose of fulfilling a characteristic condition in the cycle (Qin et al, 2007). The most important parts on the level of individual components are:

- Visual module. Its purpose is identifying objects in visual field;
- Motor module is used in the process of continual identification of motoric actions of interface users. The system recognizes motoric functions such as pressing a mouse button or a key on the keyboard;
- Goal module preserves the condition of achieved goals as well as all interactions performed on the level of individual modules (Qin et al, 2007).

The information are encapsulated within Goal Module as well as the information of all other previously mentioned components of the system. The communication flow is enabled through buffers and it can be parallel or asynchronous. Each module has its own buffer while the information encapsulated within a module are transferred by firing production based on chunks inside a buffer. The buffers of individual modules at a certain point in time can contain only one chunk of information. Also, only one "production rule" can be fired in one cycle of the process (Qin at al, 2007).

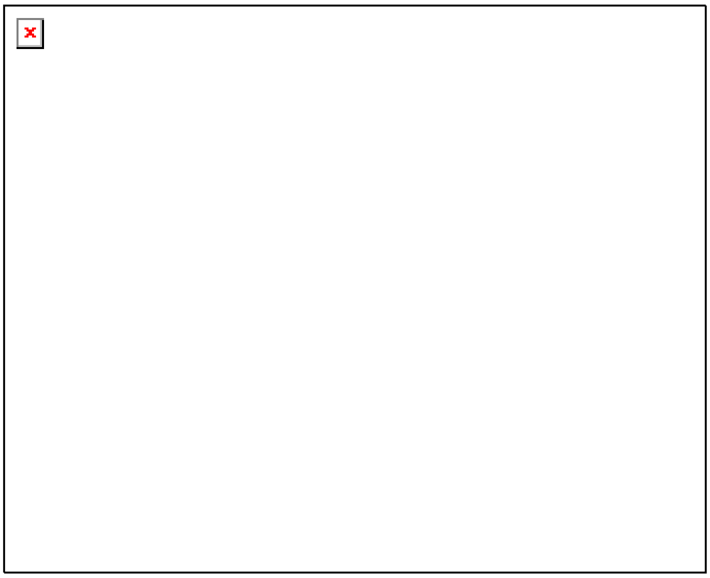

Figure 2. ACT-R model

In the interpretation of basic theoretical assumptions of ACT-R theory so far the significance and role of declarative forms of knowledge have been pointed out. In the context of terms it's been said that declarative forms of knowledge are parts, particles, "chunks" within the system. "Chunks" are, therefore, categories determined by the structure of "slots". Slots are, however, its attributes (Qin et al, 2007.)

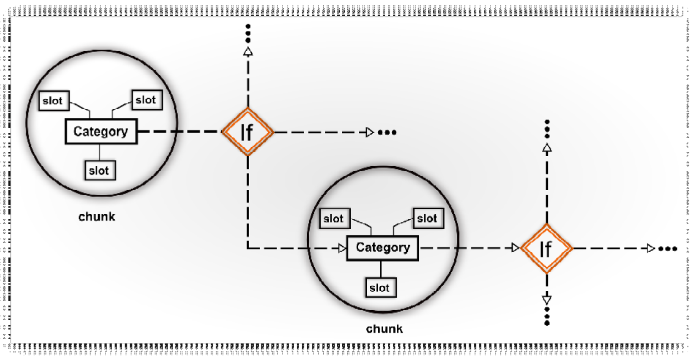

Figure 3. The structure of declarative and procedural representation within the system

Cognitive tutors are developed in specific domains, so, parameters of declarative and procedural entities depend on the complexity of the matter for which the system is made. The system must have an inside mechanism for referencing to every single entity in a declarative form (chunk). For these purposes unique identifiers which follow Lisp semantics rules for signifying and giving orders within the system are used. Behaviour control is achieved through the application of an adequate Production Rules set inside a cycle. This is a set of if/then declarations. The course of cycles of mastering teaching content is determined by the set of if/then declarations. (Qin et al, 2007).

THE ANALYSIS OF COGNITIVE TUTOR EFFICIENCY

Illustration 1. The study was conducted during the school year of 2002 – 2003 in the Miami-Dade School District (within ten schools) where the efficiency of using Cognitive Algebra Tutor was measured. The samples were collected from 6,000 examinees and their achievements were measured at the final FCAT test. The results of the study indicate that examinees of the experimental group showed more improvement in comparison to the control group which had attended the Algebra 1 program in the traditional group study. The results of the study indicate that 35.7% of the examinees of the experimental group successfully passed the test in comparison to the control group where passing score rate was only 10.9% (Sarkis, 2004).

THE ANALYSIS OF GEOMETRY COGNITIVE TUTOR EFFICIENCY

Illustration 2. In 2002, Aleven & Koedinger conducted an analysis for the purpose of testing hypothesis which states that problem-solving practice by using Cognitive Tutor can lead to a deeper understanding the subject matter if the system expects relevant explanations & procedures for solving problem from students.

In this study, the efficiency of AI Cognitive Geometry Tutor was examined in an experimental environment. The research was conducted by using the Cognitive Geometry Tutor for the purpose of testing 41 participants aged between 15 and 16 years. Two group of respondents where formed based on their previous achievements in geometry, theorems and definitions in order to form a cohesive group. The selected participants were divided into two groups. The purpose of this division was to determine the difference in the level of achievement of those students who had used the version of Cognitive Geometry Tutor which supports self-explanation compared to the version which operates in problem-solving mode. All respondents were tested with preliminary tests in order to determine the initial level knowledge of algebra. 24 Out of 41 respondents successfully finished their tests. 13 out of total number of participants finished their tests by applying Cognitive Tutor in the problem-solving mode and the other 11 used self-explanation mode. The rest of the participants didn't finish tests successfully because of the lack of time which had been limited. In the further course of the experiment, during the semester, examinees attended regular classes every day of the week (one traditional class and one class of solving problems by using Cognitive Tutor). After every lesson the examinees were tested in order to determine the difference between their achievements in the traditional teaching regime and, later on, after the work with Cognitive Tutor. It was found that the examinees in Self-explanation group accomplished a bit higher level of achievement in comparison to Problem-solving group (83.3 in comparison to 83.3 or $f(1.22) = 1.38$, $p= .25$) which is a statistically non-significant result.

In the context of time it was realized that Self-explanation group spends 18% more time in comparison to Problem-solving group when solving problems but in the end this led to better results. It can be concluded that working with Cognitive Tutor enables an adequate assistance with explanations of procedural principles of solving problems which leads to a better understanding of teaching material along with greater achievements (Aleven & Koedinger, 2002).

PSEUDO TUTORS

Long-term researches and work on the development of intelligent tutor systems have shown that there are many empiric indicators pointing out at the fact that their application affects the improvement of the level of teaching material mastering in qualitative sense. However, it's been determined that shaping and development of teaching content in the intelligent tutors' systems environment is a very complex and long process which demands a well understanding of AI programming concept. Contrary to AI tutors, Pseudo Tutors are a specific kind of authoring tools which don't require the application of AI programming for the shaping of teaching content. Pseudo Tutors can reduce the time needed for the development of the educational system which will mimic the characteristics of Intelligent Tutors (Aleven, McLaren, Sewall and Koedinger, 2006).

According to the definition of a group of authors "Pseudo Tutor is an educational system that emulates intelligent tutor behavior, but does so without using AI code to produce that behavior" (Aleven et al. 2006). Pseudo tutors are able to mimic some of the characteristics of complex AI tutors.

The goal of a research was to investigate possibilities for the application of software tools (CATT - Cognitive Tutor Authoring Tools) for the development of (Pseudo) AI tutors. In the research a set of key characteristics was found: Pseudo Tutor helps students in the process of building relevant contextual knowledge by giving a timely feedback, alternative instructions for knowledge improvement as well as alternative paths through the teaching content. Strictly technically speaking, the conceptual structure of modern cognitive tutors is accomplished through the application of "Behavioral Recording" tools which enable building an adequate graphic interactive user interface (Aleven et al. 2006).

THE ANALYSIS OF PSEUDO TUTORS EFFICIENCY

Illustration 3. The research of pseudo tutors efficiency was conducted in the domain of instruction efficiency of LSAT Analytic Logic Tutor (Aleven et al. 2006). There were 30 participants divided into two groups. The group made of all participants was cohesive, there were no significant oscillations in the level of achievement and knowledge of analytic logic. The control group was made of 30 students who were given one hour to learn the teaching material on the previously mentioned subject, After 40 minute of practice the correct results were formed within the control group, while the experimental group used LSAT Analytic Logic Tutor during the same period of time. After the end of learning the teaching material both control and experimental group were subjected to test of knowledge. The experimental group results were statistically significant pointing at the fact that the application of LSAT Analytic Logic Tutor affects positively the improvement of learning teaching content in both qualitative and quantitative sense. (12.1 +- 2.4 +- 2.3, $t(28) = 2.06$, $p < .05$).

DISCUSSION AND CONCLUSIONS

Empiric results in the domain of Cognitive Tutors' efficiency research point out to the fact that the applying the concept "learning by doing" can increase the level of achievement in learning in comparison to traditional form of teaching. However, the essence of the application of Cognitive Tutors in traditional teaching is not directed only towards the increasing of effective knowledge; it connects the speed of knowledge absorption and understanding of the theoretical concepts in a certain domain with the purpose of forming the ability of applying the learned facts when solving problems. Finally, one of the most important roles of Cognitive Tutors is to contribute the long term retention of knowledge. With Cognitive Tutors this is achieved by combining model-tracing and the architectural conception of ACT-R theory with other cognitive mechanisms and principles which are discussed in this paper.

The effect of long term, complete mastering of knowledge content is achieved by moving from declarative facts towards practical problem solving. Many years of work and research of many experts in the domain of artificial intelligence application, cognitive psychology, information technologies and other relevant sciences are invested into the improvement of cognitive tutors' possibilities which remain restricted by the complexity of their own development and other boundaries caused by specific limitation of a certain domain for they are made.

General characteristics of all rule-based systems show that the time needed for the development of such systems can't always justify its means. This makes some researchers' tendencies to develop the organization of Cognitive Tutors' architecture by applying modular approach implying clear separation of the content of a domain and the functional application set of Cognitive Tutors quite understandable. With the several decades' development of ITS much has been accomplished so far in the fields of their development, yet, some important questions remain unanswered.

In comparison with the first (primitive) forms of AI tutors, the development path of cognitive tutors have shown that the mechanisms such as model tracing can increase the flexibility of the system itself, and all possible deviations from the predefined path are not critical as before for the sake of system functionality; now it is relatively easier to manage declarative knowledge, and with the development of new authoring tools that were discussed in this study it is possible to significantly reduce the time required for the authoring process of the systems that can mimic some characteristics of AI tutors. However, beside declarative representations of knowledge the conceptual purpose of all cognitive tutors still strongly relies on procedural mechanisms for student behaviour "prediction" in the process of mastering the subject matter.

Finally, cognitive tutors based on model-tracing mechanisms still suffer from the same old limitations that can be described as inefficiency to adapt to a wide domain range of fields. Therefore, most of these systems, after being created, remain functional in a specific domain only.

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